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LETTER TO THE EDITOR

Single-mode excited entangled coherent states

Lan Xu and Le-Man Kuang[1]

Department of Physics, Hunan Normal University, Changsha 410081, People's Republic of China

E-mail: lmkuang@hunnu.edu.cn

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Abstract
We introduce a new kind of continuous-variable-type entangled pure states, called single-mode excited entangled coherent states (SMEECSs), which are obtained through actions of a creation operator of a single-mode optical field on the ECSs. We study the mathematical properties and entanglement characteristics of the SMEECSs, and investigate the influence of photon excitations on quantum entanglement. It is shown that the SMEECSs form a type of cyclic representation of the Heisenberg–Weyl algebra. It is found that the photon excitations seriously affect the entanglement character of the SMEECSs. We also show how such states can be produced by using cavity QED and quantum measurements.

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1. Introduction

Quantum state superposition and entanglement can be used to process information in non-classical ways. Entanglement is a direct consequence of the superposition principle of quantum states applied to composite systems. An essential feature of quantum entanglement is that a measurement performed on one part of the system determines the state of the other, whatever the distance between them. For decades, quantum entanglement has been the focus of much work in the foundations of quantum mechanics, being particularly with quantum non-separability, the violation of Bell's inequalities, and the so-called Einstein–Pololsky–Rosen (EPR) paradox. Beyond this fundamental aspect, creating and manipulating of entangled states are essential for quantum information applications. Among these applications are quantum computation [1, 2], quantum teleportation [3, 4], quantum dense coding [5, 6], quantum cryptography [7], and quantum positioning and clock synchronization [8]. Hence, quantum entanglement has been viewed as an essential resource for quantum information processing.

In recent years, much attention has been paid to continuous variable quantum information processing [9–23] in which continuous-variable-type entangled pure states play a key role.

[1] Author to whom any correspondence should be addressed.

For instance, two-state entangled coherent states (ECS) are used to realize efficient quantum computation [10] and quantum teleportation [11]. Two-mode squeezed vacuum states have been applied to quantum dense coding [12]. In particular, following the theoretical proposal of [13], continuous variable teleportation has been experimentally demonstrated for coherent states of a light field [14] by using entangled two-mode squeezed vacuum states produced by parametric down-conversion in a sub-threshold optical parametric oscillator. Therefore, it is an interesting topic to create and apply continuous-variable-type entangled pure states. On the other hand, a coherent state is the simplest continuous-variable state which is the closest analogue to a classical light field and exhibits a Poisson photon number distribution. Coherent states possess well defined amplitude and phase, whose uncertainties are the minimum permitted by the Heisenberg uncertainty principle. Based on coherent states, two types of continuous-variable states, called photon-added coherent states [24] and entangled coherent states [25], have been introduced and shown to have wide applications in both quantum physics [26] and quantum information processing [10, 11, 23, 27].

The purpose of this letter is to introduce a new kind of continuous-variable entangled states on the basis of coherent states, called single-mode excited entangled coherent states (SMEECSs), which are obtained through actions of a creation operator of a single-mode optical field on the ECSs. We shall study the mathematical properties and entanglement characteristics of SMEECSs, and investigate the influence of photon excitations on quantum entanglement. This letter is organized as follows. In section 2, we present the SMEECSs under our consideration. In section 3, we calculate the amount entanglement and analyse entanglement character for the SMEECSs. In section 4, we show how to produce the SMEECSs through laser–atom interactions and quantum measurement. We shall conclude this letter with discussions and remarks in the last section.

2. Single-mode excited entangled coherent states

In this section, we present the form of the SMEECSs and discuss their mathematical properties. We begin with the following two-mode ECSs:

$$|\Psi_{\pm}(\alpha,0)\rangle = \mathcal{N}_{\pm}(\alpha,0)(|\alpha,\alpha\rangle \pm |-\alpha,-\alpha\rangle), \tag{1}$$

where $|\alpha,\alpha\rangle = |\alpha\rangle \otimes |\alpha\rangle$ with $|\alpha\rangle = D(\alpha)|0\rangle$ being the usual Glauber coherent state defined by the action of the displacement operator $D(\alpha) = \exp(\alpha\hat{a}^{\dagger} - \alpha^{*}\hat{a})$ upon the vacuum state $|0\rangle$. The normalization constants are given by

$$\mathcal{N}_{\pm}^{-2}(\alpha,0) = 2[1 \pm \exp(-4|\alpha|^2)]. \tag{2}$$

For convenience, we denote the first and second modes in two-mode ECSs given by equation (1) by modes a and b, respectively. Then we consider m-photon excitations of the single mode a in the ECSs, and introduce the SMEECSs defined by

$$|\Psi_{\pm}(\alpha,m)\rangle = \mathcal{N}_{\pm}(\alpha,m)\hat{a}^{\dagger m}(|\alpha,\alpha\rangle \pm |-\alpha,-\alpha\rangle), \qquad (m \neq 0). \tag{3}$$

It is straightforward to calculate the normalization constants equation (3). We find them to be

$$\mathcal{N}_{\pm}^{-2}(\alpha,m) = 2m![L_m(-|\alpha|^2) \pm \mathrm{e}^{-2|\alpha|^2} L_m(|\alpha|^2)], \qquad (m \neq 0) \tag{4}$$

where $L_m(x)$ is the Laguerre polynomial of order m defined by

$$L_m(x) = \sum_{n=0}^{m} \frac{(-1)^n m! x^n}{(n!)^2 (m-n)!}. \tag{5}$$

In the derivation of the equation (4), we have used the following expressions:

$$\langle\alpha|\hat{a}^m\hat{a}^{\dagger m}|\alpha\rangle = m!L_m(-|\alpha|^2), \qquad \langle\alpha|\hat{a}^m\hat{a}^{\dagger m}|-\alpha\rangle = m!L_m(|\alpha|^2), \qquad (m \neq 0). \tag{6}$$

Making use of the following expression,

$$\hat{a}^{\dagger m}|\alpha,\alpha\rangle = \mathrm{e}^{-|\alpha|^2}\sum_{r,s=0}^{\infty}\frac{\sqrt{(r+m)!}}{r!\sqrt{s!}}\alpha^{r+s}|r+m,s\rangle, \tag{7}$$

we can obtain the number-state representation of SMEECSs as follows:

$$|\Psi_{\pm}(\alpha,m)\rangle = \mathcal{N}_{\pm}(\alpha,m)\,\mathrm{e}^{-|\alpha|^2}\sum_{r,s=0}^{\infty}\frac{\sqrt{(r+m)!}}{r!\sqrt{s!}}\alpha^{r+s}[1\pm(-1)^{r+s}]|r+m,s\rangle, \tag{8}$$

which implies that the SMEECSs $|\Psi_{\pm}(\alpha,m)\rangle$ are two truncations of the two-mode ECS given by equation (1) with respect to the mode a, in which all the terms related to the Fock states of the mode a: $|0\rangle, |1\rangle, |2\rangle, \ldots, |m-1\rangle$ are removed.

If we introduce the following normalized states with respect to the mode a,

$$\begin{aligned}|d(\pm\alpha,m)\rangle &= d(\alpha,m)\hat{a}^{\dagger m}|\pm\alpha\rangle\\ &= d(\alpha,m)\sum_{p=0}^{m}\frac{m!}{(m-p)!\sqrt{p!}}(\pm\alpha^*)^{m-p}D(\pm\alpha)|p\rangle,\end{aligned} \tag{9}$$

which is a superposition state of m displaced number states with the normalized coefficients given by

$$d^{-2}(\alpha,m) = m!L_m(-|\alpha|^2). \tag{10}$$

Then the SMEECSs $|\Psi_{\pm}(\alpha,m)\rangle$ in terms of four normalized states can be written as

$$|\Psi_{\pm}(\alpha,m)\rangle = \mathcal{N}_{\pm}(\alpha,m)d^{-1}(\alpha,m)[|d(\alpha,m)\rangle\otimes|\alpha\rangle \pm |d(-\alpha,m)\rangle\otimes|-\alpha\rangle]. \tag{11}$$

It is interesting to note that the SMEECSs $|\Psi_{\pm}(\alpha,m)\rangle$ are eigenstates of the $2k$-th power of the annihilation operator of the mode b with eigenvalues α^{2k},

$$\hat{b}^{\dagger 2k}|\Psi_{\pm}(\alpha,m)\rangle = \alpha^{2k}|\Psi_{\pm}(\alpha,m)\rangle, \qquad (k=1,2,3,\ldots), \tag{12}$$

which means that the set of the SMEECSs $\{|\Psi_{\pm}(\alpha,m)\rangle\}$ forms a kind of representations of the Heisenberg–Weyl algebra spanned by $\hat{b}^{\dagger}$, $\hat{b}$, and $\hat{b}^{\dagger}\hat{b}$, we call it the excited ECS representation. $\{|\Psi_{+}(\alpha,m)\rangle\}$ and $\{|\Psi_{-}(\alpha,m)\rangle\}$ are the two subspaces of the representation. It can be shown that each subspace of the representation may be transformed to another by the actions of the odd-number power of the annihilation operator $\hat{b}$,

$$\begin{aligned}\hat{b}^{\dagger 2k+1}|\Psi_{+}(\alpha,m)\rangle &= \alpha^{2k+1}\mathcal{N}_{+}(\alpha,m)\mathcal{N}_{-}^{-1}(\alpha,m)|\Psi_{-}(\alpha,m)\rangle,\\ \hat{b}^{\dagger 2k+1}|\Psi_{-}(\alpha,m)\rangle &= \alpha^{2k+1}\mathcal{N}_{-}(\alpha,m)\mathcal{N}_{+}^{-1}(\alpha,m)|\Psi_{+}(\alpha,m)\rangle,\end{aligned} \tag{13}$$

which implies that the excited ECS representation is a type of cyclic representation [28, 29]. The orthogonality relations of the representation can be written as

$$\begin{aligned}\langle\Psi_{\pm}(\alpha,m)|\Psi_{\pm}(\beta,n)\rangle = \mathcal{N}_{\pm}(\alpha,m)\mathcal{N}_{\pm}(\beta,n)[&\langle\alpha|\beta\rangle A_{mn}(\alpha,\beta) + \langle-\alpha|-\beta\rangle A_{mn}(-\alpha,-\beta)\\ &\pm\langle\alpha|-\beta\rangle A_{mn}(\alpha,-\beta) \pm \langle-\alpha|\beta\rangle A_{mn}(-\alpha,\beta)],\end{aligned} \tag{14}$$

$$\begin{aligned}\langle\Psi_{\pm}(\alpha,m)|\Psi_{\mp}(\beta,n)\rangle = \mathcal{N}_{\pm}(\alpha,m)\mathcal{N}_{\mp}(\beta,n)[&\langle\alpha|\beta\rangle A_{mn}(\alpha,\beta) \mp \langle\alpha|-\beta\rangle A_{mn}(\alpha,-\beta)\\ &\pm\langle-\alpha|\beta\rangle A_{mn}(-\alpha,\beta) - \langle-\alpha|-\beta\rangle A_{mn}(-\alpha,-\beta)],\end{aligned} \tag{15}$$

where $\langle\alpha|\beta\rangle = \exp[-(|\alpha|^2+|\beta|^2)/2+\alpha^*\beta]$, and we have introduced

$$A_{mn}(\alpha,\beta) = \langle\alpha|\hat{a}^m\hat{a}^{\dagger n}|\beta\rangle. \tag{16}$$

3. The amount of entanglement of the SMEECS

In this section we calculate the amount of entanglement of the SMEECSs and investigate the influence of the single-mode photon excitations on the entanglement of the SMEECSs. From equation (11), we can see that the SMEECSs are two-component entangled states. The degree of quantum entanglement of the two-state entangled states can be measured in terms of the concurrence [15, 27, 30] which is generally defined for discrete-variable entangled states to be [30]

$$\mathcal{C} = |\langle\Psi|\sigma_y \otimes \sigma_y|\Psi^*\rangle|, \tag{17}$$

where $|\Psi^*\rangle$ is the complex conjugate of $|\Psi\rangle$. The concurrence equals one for a maximally entangled state.

For continuous-variables-type entangled states like (11), we consider a general bipartite entangled state

$$|\psi\rangle = \mu|\eta\rangle \otimes |\gamma\rangle + \nu|\xi\rangle \otimes |\delta\rangle, \tag{18}$$

where $|\eta\rangle$ and $|\xi\rangle$ are *normalized* states of subsystem 1 and $|\gamma\rangle$ and $|\delta\rangle$ *normalized* states of subsystem 2 with complex μ and ν. After normalization, the bipartite state $|\Psi\rangle$ can be expressed as

$$|\Psi\rangle = \frac{1}{N}[\mu|\eta\rangle \otimes |\gamma\rangle + \nu|\xi\rangle \otimes |\delta\rangle], \tag{19}$$

where the normalization constant is given by

$$N^2 = |\mu|^2 + |\nu|^2 + 2\,\mathrm{Re}(\mu^*\nu p_1 p_2^*), \qquad p_1 = \langle\eta|\xi\rangle, \quad p_2 = \langle\delta|\gamma\rangle. \tag{20}$$

Through transforming continuous-variables-type components to discrete orthogonal basis and making use of a Schmidt decomposition [31], one can find the concurrence of the entangled state (19) to be [15, 32]

$$\mathcal{C} = \frac{2|\mu||\nu|}{N^2}\sqrt{(1-|p_1|^2)(1-|p_2|^2)}. \tag{21}$$

For the case of the no-photon excitation ECSs (i.e., $m = 0$), making use of equations (1) and (2) from equations (19)–(21), we can find that the concurrence is given by

$$\mathcal{C}_-(\alpha, 0) = 1, \qquad \mathcal{C}_+(\alpha, 0) = \frac{1 - \mathrm{e}^{-4|\alpha|^2}}{1 + \mathrm{e}^{-4|\alpha|^2}}, \tag{22}$$

which implies that the degree of entanglement of the ECS $|\Psi_-(\alpha, 0)\rangle$ is independent of the state parameter α, and it is a maximally entangled state while the amount of entanglement of the ECS $|\Psi_+(\alpha, 0)\rangle$ is less than that of the ECS $|\Psi_-(\alpha, 0)\rangle$, but it increases with the values of the state parameter α. In figure 1, we plot the concurrence $\mathcal{C}_+(\alpha, 0)$ for different values of $|\alpha|^2$. From figure 1 we can see that the concurrence $\mathcal{C}_+(\alpha, 0)$ increases with $|\alpha|^2$, and the state $|\Psi_+(\alpha, 0)\rangle$ approaches the maximally entangled coherent state with $\mathcal{C}_+(\alpha, 0) \approx 1$ for the strong filed case of the large $|\alpha|^2$.

When there exist photon excitations ,i.e., $m \neq 0$, the SMEECS is given by equation (11). From equations (20) and (21), we find the corresponding concurrence to be

$$\mathcal{C}_-(\alpha, m) = \frac{\left[\left(1 - \mathrm{e}^{-4|\alpha|^2}\right)\left(L_m^2(-|\alpha|^2) - L_m^2(|\alpha|^2)\right)\right]^{1/2}}{L_m^2(-|\alpha|^2) - \mathrm{e}^{-2|\alpha|^2} L_m^2(|\alpha|^2)}, \tag{23}$$

$$\mathcal{C}_+(\alpha, m) = \frac{\left[\left(1 - \mathrm{e}^{-4|\alpha|^2}\right)\left(L_m^2(-|\alpha|^2) - L_m^2(|\alpha|^2)\right)\right]^{1/2}}{L_m^2(-|\alpha|^2) + \mathrm{e}^{-2|\alpha|^2} L_m^2(|\alpha|^2)}. \tag{24}$$

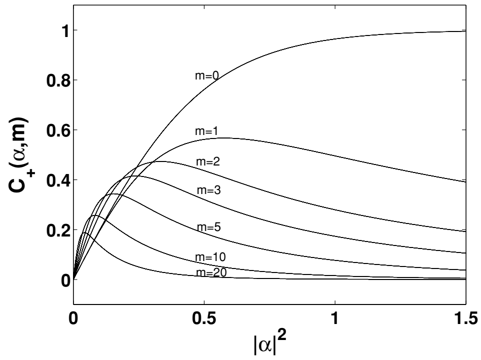

Figure 1. The concurrence of the SMEECS $|\Psi_{+}(\alpha, m)\rangle$ versus $|\alpha|^2$ for the different photon excitations with $m = 0, 1, 2, 3, 5, 10$, and 20, respectively.

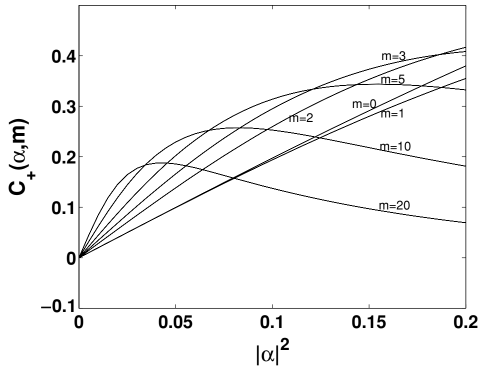

Figure 2. The concurrence of the SMEECS $|\Psi_{+}(\alpha, m)\rangle$ versus $|\alpha|^2$ for the different photon excitations with $m = 0, 1, 2, 3, 5, 10$, and 20, respectively.

In order to observe the influence of the photon excitations on the quantum entanglement of the SMEECS $|\Psi_{+}(\alpha, m)\rangle$ for different strength regimes of the optical fields, we plot the concurrence $\mathcal{C}_{+}(\alpha, m)$ for different values of $|\alpha|^2$ and different photon excitation number m in figure 1. Figure 1 indicates that the SMEECS has different entanglement characters in different strength regimes of the optical fields. From figure 1, we can see the concurrence curve of each SMEECS $|\Psi_{+}(\alpha, m)\rangle$ $(m \neq =0)$ exhibits a peak. These peaks move to the left-hand side with increasing the photon excitation number m while the height of the peaks decreases with increasing m. On the left-hand side of the peak, the concurrence rises with increasing the optical strength $|\alpha|^2$; however, on the right-hand side of the peak, the concurrence decreases with increasing $|\alpha|^2$. In the weak field regime, the concurrence of the SMEECS exhibits an interesting characteristic. In order to see this, in figure 2 we plot the concurrence $\mathcal{C}_{+}(\alpha, m)$ in the weak field regime of $|\alpha|^2 < 0.03$ for different photon excitation number m, it can be seen that the concurrence increases with the photon excitation number m, and linearly enhances with the strength of the optical fields $|\alpha|^2$. These results can be confirmed analytically. In fact, in the weak field regime of $|\alpha|^2 < 0.03$, from equation (24), we can obtain an approximate analytic expression of the concurrence $\mathcal{C}_{+}(\alpha, m) \approx \sqrt{m}|\alpha|^2$. From figure 1 and figure 2 we can see that in the intermediate field regime entanglement character of the SMEECS $|\Psi_{+}(\alpha, m)\rangle$

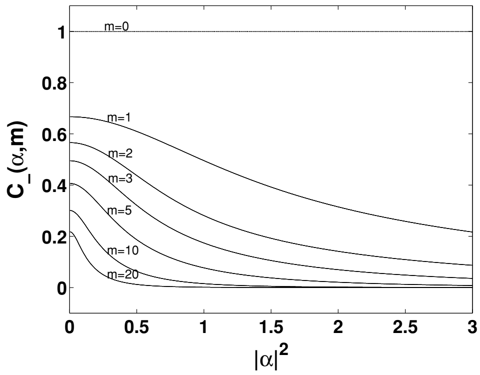

Figure 3. The concurrence of the SMEECS $|\Psi_-(\alpha, m)\rangle$ versus $|\alpha|^2$ for the different photon excitations with $m = 0, 1, 2, 3, 5, 10$, and 20, respectively.

is more complex than that in the other regimes. In the strong filed regime, figure 1 shows that the concurrence of the no-excitation ECS $|\Psi_+(\alpha, 0)\rangle$ enhances with $|\alpha|^2$, and it approaches its maximal value 1 when $|\alpha|^2$ tends the infinity. However, the SMEECS exhibits a quite different character since the concurrence of the SMEECS does decrease with $|\alpha|^2$ in the strong filed regime. Especially, the concurrence tends to zero when $|\alpha|^2 \to \infty$.

Then we numerically investigate the entanglement properties of the SMEECHS $|\Psi_-(\alpha, m)\rangle$. We plot the concurrence $\mathcal{C}_-(\alpha, m)$ for different values of $|\alpha|^2$ and different photon excitation number m in figure 3. From figure 3 we can see that the entanglement character of the SMEECS $|\Psi_-(\alpha, m)\rangle$ with photon excitations ($m \neq 0$) is quite different that of the ECS without photon excitation ($m = 0$). The concurrence of the ECS $|\Psi_-(\alpha, 0)\rangle$ is independent of the strength $|\alpha|^2$. However, the concurrence of the former is dependent of the strength $|\alpha|^2$, and it decreases with increasing the number of the photon excitations m and $|\alpha|^2$. This implies that the photon excitations suppress the entanglement amount of the SMEECS $|\Psi_-(\alpha, m)\rangle$.

4. Generation of the SMEECSs

In the previous sections we have seen interesting mathematical and entanglement properties of the SMEECSs. The question now arises of how such states can be generated in practice. In what follows, we present a possible scheme to produce them from the two mode ECSs through atom–field interaction.

Consider an interaction between a two-level atom with a cavity field. The atom makes a transition from the excited state $|e\rangle$ to the ground state $|g\rangle$ by emitting a photon. In the interaction picture, the Hamiltonian of resonant interaction is given by

$$\hat{H} = \hat{\sigma}_+\hat{a} + g^*\hat{\sigma}_-\hat{a}^\dagger, \tag{25}$$

where $\hat{\sigma}_+$ and $\hat{\sigma}_-$ are the Pauli operator corresponding to the two-level atom, $\hat{a}^\dagger$ and $\hat{a}$ are the creation and annihilation operator of the field mode a, g is the coupling constant.

Suppose that the atom is initially in the excited state and the two filed modes is initially in the two-mode ECS given by equation (1), but only the mode a interacts with the atom. Then, for the weak coupling case, the state of the atom–field system at time t can be approximated by

$$|\psi(t)\rangle \approx |\Psi_\pm(\alpha, 0)\rangle \otimes |e\rangle - \mathrm{i}\hat{H}t|\Psi_\pm(\alpha, 0)\rangle \otimes |e\rangle, \tag{26}$$

which is approximately valid for interaction times such that $gt \ll 1$. Making use of equation (24), one can reduce (26) to

$$|\psi(t)\rangle \approx |\Psi_{\pm}(\alpha, 0)\rangle \otimes |e\rangle - \mathrm{i}(g^{*}t)\hat{a}^{\dagger}|\Psi_{\pm}(\alpha, 0)\rangle \otimes |g\rangle, \tag{27}$$

which indicates that if the atom is detected to be in the ground state $|g\rangle$, then after normalization the state of the two optical fields is reduced to the SMEECS $|\Psi_{+}(\alpha, 1)\rangle$ given by equation (3). If we consider a succession of m atoms through the cavity and if we detect all the atoms in the ground state $|g\rangle$, then the state of the two optical fields is reduced to the desired state, the SMEECS with m-photon excitations. Hence, we can, in principle, produce the SMEECS $|\Psi_{\pm}(\alpha, m)\rangle$.

5. Concluding remarks

We have introduced the SMEECSs through actions of a creation operator of a single-mode optical field on the ECS. We have investigated the mathematical properties and entanglement characteristics of the SMEECSs, and discussed the influence of photon excitations on quantum entanglement. We have also shown how such states can be produced in the laser–atom interaction by using cavity QED and quantum measurements. It has been shown that the SMEECSs form a new type of cyclic representation of the Heisenberg–Weyl algebra, i.e., the excited entangled-state representation. It has been found that the photon excitations affect seriously entanglement character of the SMEECSs in the weak field case. We have observed the much rich entanglement properties of the SMEECSs. It has been found that, in most cases, the photon excitations lead to the decrease of the entanglement amount of the SMEECSs. However, we have found that, in the weak field regime, the photon excitations may enhance the amount of entanglement for the SMEECS $|\Psi_{-}(\alpha, m)\rangle$. This provides us with a new entanglement resource which can be applied not only to quantum information processing with continuous variables [9] such as quantum teleportation of photon-added coherent-state-type quantum states [24] and quantum cryptography, but also to studies of fundamental problems such as quantum non-locality and violation of Bell inequalities. Indeed, a further investigation on non-classical characters of the SMEECSs and their applications to quantum information processing would be interesting, but it is beyond the scope of the present paper. We will discuss them elsewhere.

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